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## Life Cycle Assessment of Land Use in Neighborhoods

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### Abstract

Urban sprawl and the increase of the built-up area have a major impact on land use. Buildings are responsible for two types of land use interventions: primary land use, i.e. the building footprint and secondary land use, associated with the resource extraction, production, transport and end-of-life treatment of construction products. However the environmental impact related to the primary land use is mostly not considered in current Life Cycle Assessment (LCA) studies of the built environment.

The purpose of this paper is to assess the environmental impact of primary land use in neighbourhoods, considering not only the footprint of buildings but also the footprint of infrastructure and open spaces. Impacts related to land occupation and transformation are evaluated based on the impact assessment methods soil organic matter (SOM) (i.e. impact on soil quality) and Eco-indicator 99 (i.e. impact on biodiversity).

An LCA study of neighbourhood models with diverse built densities, i.e. consisting of detached houses, semi-detached houses, terraced houses to compact apartment blocks, is performed. Moreover, buildings are simulated using combinations of building elements, from solid to timber frame structure.

The results reveal the high contribution of primary land use to the neighbourhood life cycle environmental impacts, especially in low built density neighbourhoods. Furthermore, the environmental impact of primary land use is in most cases higher than secondary land use. Based on this analysis, it is recommended to include the assessment of primary land use in neighbourhood LCA, especially in studies comparing different built densities.

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**Keywords:** Built density; Neighbourhood layout; Primary land use; Secondary land use; Land occupation; Land transformation

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## 1. Introduction

Urban sprawl and the increase of the built-up area have a major impact on land use. Between 1980 and 2000, the built-up area in Europe increased by about 20% [1]. Buildings are responsible for two types of land use interventions: primary land use, i.e. the building footprint and secondary land use, associated with the resource extraction, production, transport and end-of-life treatment of construction products [2]. However, the environmental impact related to the primary land use is mostly not considered in current Life Cycle Assessment (LCA) studies of the built environment. In Allacker et al. (2014) [2], the primary land use of a detached house in Belgium is evaluated, using different land use impact assessment models. This study reveals the importance of including primary land use in a building LCA, as the impact of primary and secondary land use are of the same order of magnitude.

The purpose of this paper is to assess the environmental impact of primary land use in neighbourhoods, considering not only the footprint of buildings but also the footprint of infrastructure and open spaces. Based on the analysis of neighbourhood models with diverse built densities, the contribution of primary land use to the neighbourhood life cycle environmental impacts is evaluated. Furthermore, the impact of the neighbourhood primary land use is compared to the secondary land use resulting from the construction products.

In the subsequent section, the methodology is presented, including a description of the LCA method, the assessment of primary land use in neighbourhoods and the analysed case studies. In section 3 the LCA results of the neighbourhood models are described. Conclusions and recommendations are formulated in the final section.

## 2. Materials and methods

### 2.1. Life Cycle Assessment (LCA)

The environmental impact assessment used in this paper is based on the LCA method developed within the MMG (“Environmental profile of building elements”) research project, commissioned by the Public Waste Agency of Flanders (OVAM)[3][4]. Within this project an evaluation method for the environmental performance of building elements is developed, specific for the Belgian context. In a recent research [5], the MMG method was extended to the neighbourhood scale level, by evaluating building clusters, in combination with the required road infrastructure.

Regarding the selected environmental indicators (Table 1), the impact categories in the MMG method include the ones defined by the EN 15804 standard [6], which are further referred to as CEN indicators. In addition, seven more impact categories are considered based on the International Reference Life Cycle Data System (ILCD) Handbook [7]. The additional impact categories are further referred to as CEN+ indicators. Concerning land use, two types of interventions are considered: land occupation and land transformation. Land occupation occurs when a specific land use type is maintained over a period of time, leading to a delay in the recovery of land to its potential natural state, while land transformation refers to a change in the land use type [2]. Within the MMG method, impacts related to land occupation and transformation are evaluated based on a combination of two impact assessment methods, such as recommended by Allacker et al. (2014) [2]: soil organic matter (SOM) of Milà i Canals [8] for the impacts on soil quality and Eco-indicator 99 [9] for the impacts on biodiversity.

Table 1. Overview of the environmental impact indicators used in the MMG LCA method [4]. A distinction is made between the CEN and CEN+ impact categories.

CEN indicators	CEN+ indicators
Global warming	Human toxicity (cancer and non-cancer effects)
Depletion of the stratospheric ozone layer	Particulate matter
Acidification of land and water sources	Ionising radiation (human health and ecotoxicity)
Eutrophication	Ecotoxicity (freshwater)
Formation of tropospheric ozone photochemical oxidants	Water scarcity
Abiotic depletion of non-fossil resources	Land use occupation (soil organic matter and biodiversity)

## Abiotic depletion of fossil resources

## Land use transformation (soil organic matter and biodiversity)

In addition to individual impact indicators, the MMG method provides an aggregated single-score indicator, expressed in a monetary value (EURO), indicating the external environmental cost. This external environmental cost is calculated by multiplying the characterised environmental impact indicators with their specific monetary value and adding these up to obtain the overall environmental cost. In this paper, the MMG monetary values of the central scenario for Western-Europe [4] are selected to calculate the environmental cost of the analysed neighbourhood models. Concerning the valuation of land use impacts (Table 2), MMG monetary values are provided for the impacts on soil organic matter, both for land occupation and land transformation. For the impacts on biodiversity, MMG monetary values are only available for land occupation, based on impacts expressed in m<sup>2</sup>a and a subdivision in three land use categories: urban, agricultural and forest land use. As the MMG monetary values for the impacts on biodiversity are not linked to the loss of species, calculated in Eco-indicator 99, an alternative valuation method, such as defined in Allacker (2010) [10], is proposed, based on the impacts expressed in PDF (Potentially Disappeared Fraction of species). In this paper, a comparison is made between the LCA results based on the original set of MMG monetary values, further referred to as MMG, and the alternative set of monetary values, further referred to as MMG\_PDF (see Table 2).

Concerning the life cycle inventory, the environmental data, used in the analysis, are based on the Ecoinvent database version 2.2 [11]. However, in order to increase the representativeness for the Belgian context, Swiss data records were adapted by replacing the Swiss electricity mix and transport processes by European corresponding processes [3].

Table 2. Overview of the land use impact indicators and their monetary values. Two scenarios for the monetary values are considered: MMG (central scenario for Western Europe) and MMG\_PDF [4][10].

Impact indicators	Unit	MMG (€/unit)	MMG_PDF (€/unit)
Land use occupation			
• Soil organic matter	kg C deficit	2.7E-06	2.7E-06
• Biodiversity	PDF*m <sup>2</sup> a		0.49
	Urban m <sup>2</sup> a	0.30	
	Agricultural m <sup>2</sup> a	6.0E-03	
	Forest m <sup>2</sup> a	2.2E-04	
Land use transformation			
• Soil organic matter	kg C deficit	2.7E-06	2.7E-06
• Biodiversity	PDF*m <sup>2</sup>		0.49

## 2.2. Assessment of primary land use in neighbourhoods

When assessing the primary land use of neighbourhoods, a distinction can be made between three interventions (Fig. 1). First, a transformation in type of land use (from A to B), such as for example from forest to urban land use, can occur at the start of the neighbourhood life cycle (t1). This transformation leads to a decrease or increase in land quality, depending on the original type of land use. The transformation impact is calculated as the difference in land quality between the original state (A) and the neighbourhood land use (B), multiplied by the land use area. Second, a specific type of land use is maintained during the neighbourhood life span (from t1 to t2), leading to an occupation impact. This occupation impact is calculated as the difference in land quality between the neighbourhood land use (B) and the (reference) natural state, multiplied by the land use area and neighbourhood life span. Third, a transformation in type of land use (from B to C), such as for example from urban land to meadow, can occur at the end of the neighbourhood life cycle (t2). However, as the land use type after the demolition of the neighbourhood is often unknown, it is assumed in this paper that no change in land use type occurs after the end-of-life, resulting in a transformation impact of zero.

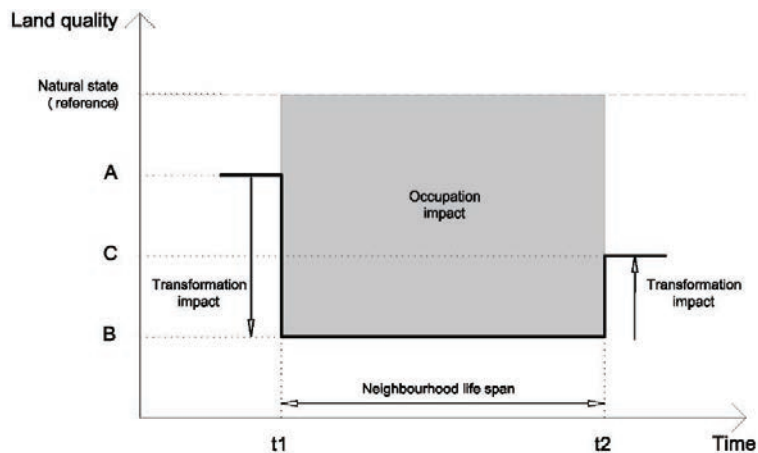


Fig. 1. Graphical representation of land use interventions in neighbourhoods, based on [12].

### 2.3. Neighbourhood models

Four neighbourhood models composed of representative Belgian dwelling types are defined (Fig. 2). These consist of respectively detached houses (Model 1), semi-detached houses (Model 2), terraced houses (Model 3) and apartments (Model 4). The models differ in built density with a Floor Space Index, ranging from 0.21 in Model 1 to 1.13 in Model 4. The dwellings are composed of standard building elements from the MMG database (see Table 3), in line with the current energy regulations in Flanders (2016) [13]. To compare the contribution of primary and secondary land use, the dwellings are simulated based on both a solid and a timber frame structure. The solid structure is composed of walls of clay building blocks and concrete floors. The timber frame consists of a wood skeleton filled with stone wool insulation. For the road infrastructure, standard road, bicycle path and footpath sections with an asphalt pavement are selected.

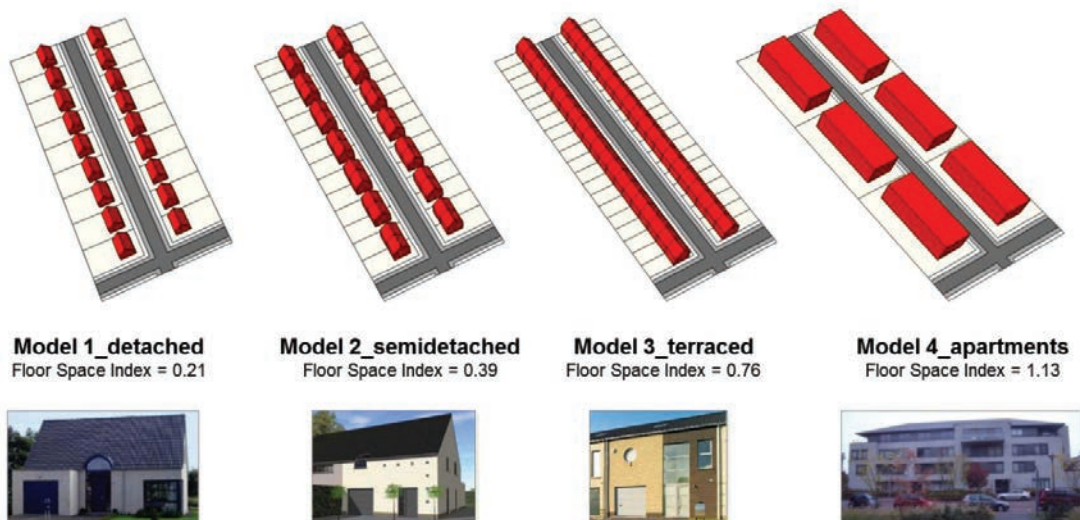


Fig. 2. Neighbourhood models based on four representative dwelling typologies for the Belgian context: detached houses (Model 1), semi-detached houses (Model 2), terraced houses (Model 3) and apartments (Model 4).

Table 3. Overview of the building elements analysed.

Building element	Solid variant	Timber variant
Floor on grade	concrete slab 15 cm – PUR foam 10 cm – screed mix – fired clay tiles	concrete slab 15 cm – PUR foam 10 cm – screed mix – parquet
External wall	facing brick – PUR board 8 cm – hollow brick 14 cm – gypsum plaster – acrylic paint	cedar planks – timber frame + stone wool 20 cm – plasterboard – acrylic paint
Loadbearing internal wall	acrylic paint – gypsum plaster – hollow brick 14 cm – gypsum plaster – acrylic paint	acrylic paint – plasterboard – timber frame + stone wool 14 cm – plasterboard – acrylic paint
Non-bearing internal wall	acrylic paint – gypsum plaster – hollow brick 9 cm – gypsum plaster – acrylic paint	acrylic paint – plasterboard – timber frame + stone wool 10 cm – plasterboard – acrylic paint
Floor	acrylic paint – gypsum plaster – concrete slab 15 cm – screed mix – fired clay tiles	acrylic paint – plasterboard – wooden beams 22 cm + stone wool – OSB – parquet
Stairs	concrete staircase – metal banister	wooden closed staircase – varnish – wooden banister
Flat roof	EPDM – PUR board 12 cm – concrete slope layer – concrete slab 15 cm – gypsum plaster – acrylic paint	EPDM – stone wool 16 cm – OSB – slope wedges – wooden beams 22 cm – plasterboard – acrylic paint
Pitched roof	Clay tiles – wood fibre board – purlins and jack rafters + stone wool 18 cm – plasterboard – acrylic paint	
Window	PVC frame – standard double-glazed ( $U=1.1 \text{ W/m}^2\text{K}$ )	painted wood frame – standard double-glazed ( $U=1.1 \text{ W/m}^2\text{K}$ )
Internal door	MDF frame – plain door	oak frame and panel

Regarding the system boundaries, a neighbourhood life span of 60 years is considered. The environmental impact is assessed over the entire life cycle, including the production, construction, use and end-of-life stage. The assessment covers the impact of the buildings and the road infrastructure. The construction and maintenance of open spaces, i.e. the gardens surrounding the buildings, are not included in the analysis. The land surface occupied by those spaces is however considered for the assessment of primary land use. Concerning the buildings, only the space delimiting elements (i.e. floors, walls, roofs, stairs, windows and doors) are assessed. The construction and maintenance of technical systems (i.e. piped and electrical services) are not considered but energy and water use are included. The energy use for heating is calculated based on the equivalent degree day method, which is a simplified approach to estimate the heating demand in buildings [10]. Energy use for appliances and lighting and water use are based on average household consumption data for Belgium [10].

Concerning the assessment of primary land use, the analysed neighbourhood models are assumed to be built on forest land. As less than 80% of the total neighbourhood area is considered to be sealed in all 4 models, the land use type “urban discontinuously built” is selected to characterize the land use of the buildings, road infrastructure and open spaces. For the model consisting of detached houses, alternatives for the original land use are evaluated, including a conversion from arable land, pasture or dump site. Furthermore the influence of the neighbourhood land use is analysed by comparing the land use categories “urban continuously built” and “urban discontinuously built”.

### 3. Results

The LCA results for the neighbourhood models, expressed in euro/m<sup>2</sup> total floor area, are shown in Fig. 3, with a distinction between the impact resulting from the building materials, energy use, water use and primary land use. The contribution of primary land use to the total neighbourhood life cycle impact depends on the built density and varies from about 5% in the model consisting of apartments (Model 4) to about 20% in the model consisting of detached houses (Model 1), based on the MMG monetary values. When using the MMG\_PDF monetary values, the contribution is even higher, ranging from about 10% in Model 4 to about 35% in Model 1. This is due to the higher valuation of land use impacts in MMG\_PDF (see Fig. 4).

The choice of the monetisation method has also an influence on the comparison between the variants in solid and timber frame structure. The neighbourhood variants in timber frame structure have a lower life cycle environmental cost, compared to the solid variants, based on MMG but a higher life cycle environmental cost based on

MMG\_PDF. The reason is again the higher valuation of land use impacts in MMG\_PDF, which has a higher influence on the environmental cost of wood-based construction products.

In order to analyse the contribution of primary versus secondary land use, the land use environmental costs of the neighbourhood models are shown in Fig. 4. The results reveal important differences depending on the monetisation method. Based on the MMG monetary values, the contribution of primary land use varies from about 85 to 95% and 70 to 90% of the total impact of land use, for respectively the solid and timber frame variants. Based on the MMG\_PDF monetary values, the contribution of primary land use is similar for the solid variants (from about 80 to 90%) but much lower for the timber frame variants (from about 30 to 65%). The reason for the high contribution of primary land use based on the MMG monetary values, is the high valuation of urban land use, compared to agricultural and forest land use (both resulting mainly from secondary land use). In MMG, the monetary value of “land use occupation, biodiversity, urban” is 1364 times higher than for “land use occupation, biodiversity, forest”, while the loss of species for urban land use (discontinuously built) is only 9 times higher than for forest land use.

Regarding the contribution of the land use impact indicators, the indicator “Land use occupation, biodiversity” is the highest contributor to the total land use environmental cost, i.e. more than 99% and from 65 to 90%, based respectively on the MMG and MMG\_PDF monetary values. The contribution of the indicator soil organic matter is negligible in all analysed cases. Although the indicator “Land use transformation, biodiversity” is not valued in MMG, it contributes from 10% to 35% of the total land use environmental cost, based on MMG\_PDF.

Finally, alternatives for the original and neighbourhood land use are evaluated for the model consisting of detached houses, composed of a solid structure. As the biodiversity impacts related to land transformation cannot be assessed when using the MMG monetary values, only the results based on MMG\_PDF are shown in Fig. 5. Concerning the original land use, a conversion from arable land, pasture or dump site results in a reduction of the total land use environmental cost of respectively 41, 36 and 29%, compared to a conversion from forest land. A conversion from arable land or pasture even leads to a negative environmental cost for the indicator “Land transformation, biodiversity”, as the number of species is higher for a discontinuously built urban land. Regarding the neighbourhood land use, an increase of about 20 to 30% of the total land use environmental cost is noticed for continuously built urban land use, compared to discontinuously built urban land use. This increase is due to higher impacts for both land transformation and occupation.

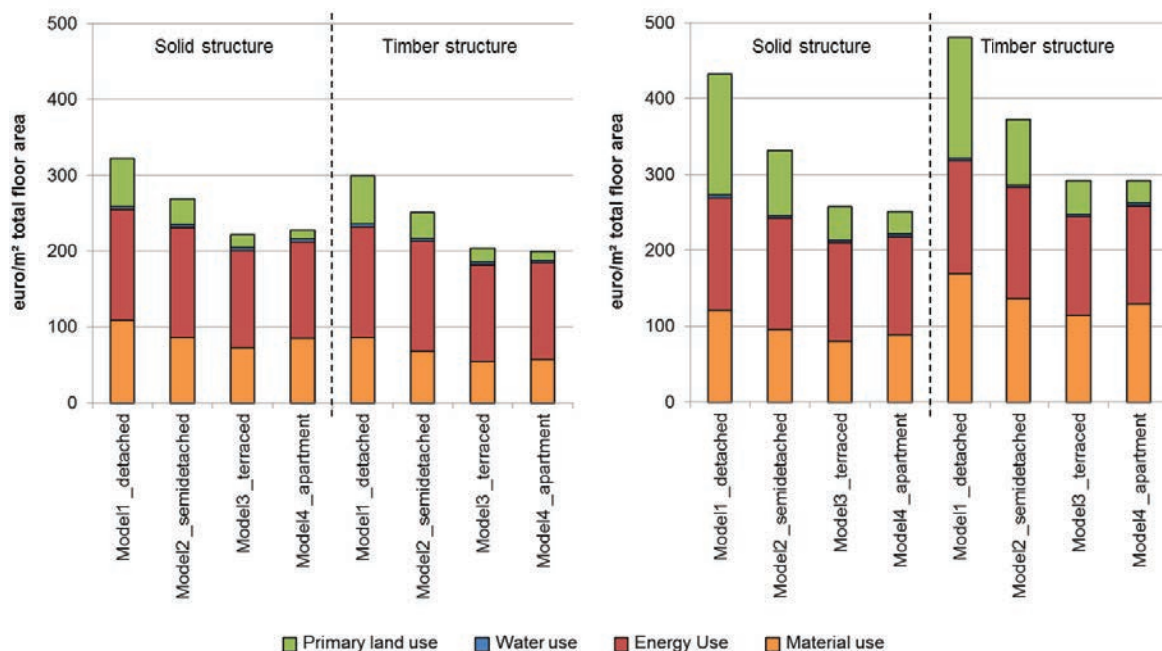


Fig. 3. Life cycle environmental cost of the neighbourhood models analysed, based on the monetary scenarios MMG (left) and MMG\_PDF (right)



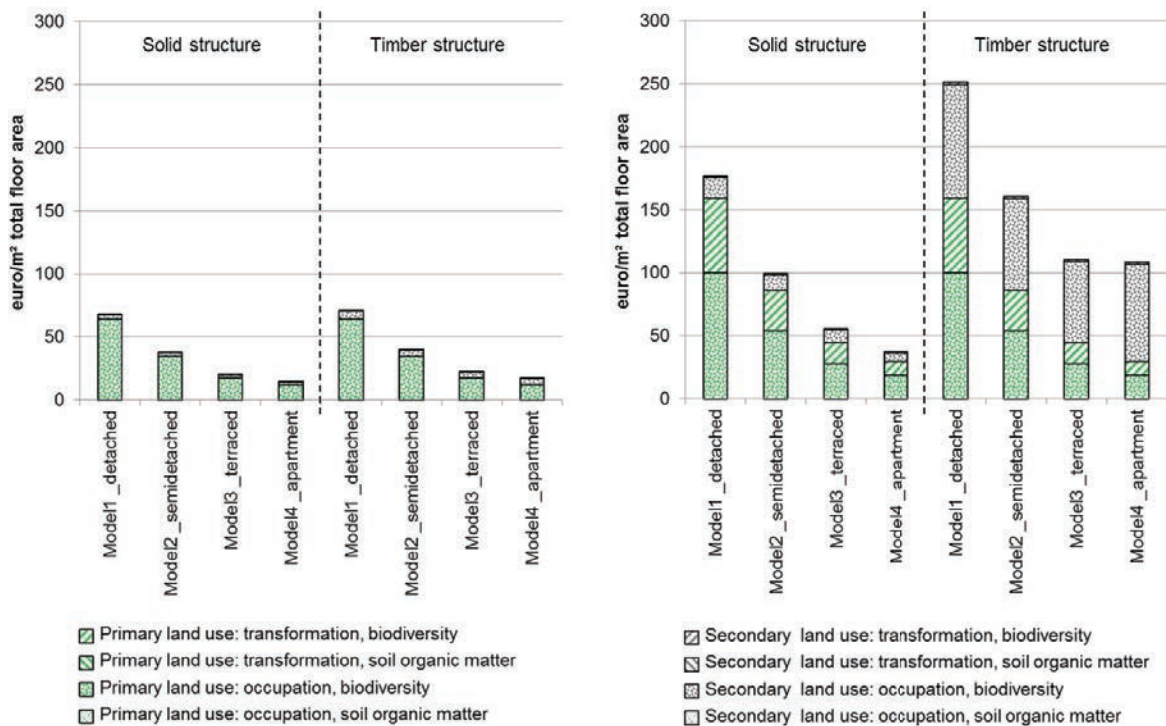


Fig. 4. Land use environmental cost of the neighbourhood models analysed, subdivided per impact indicator. The results are calculated based on the monetary scenarios MMG (left) and MMG\_PDF (right)

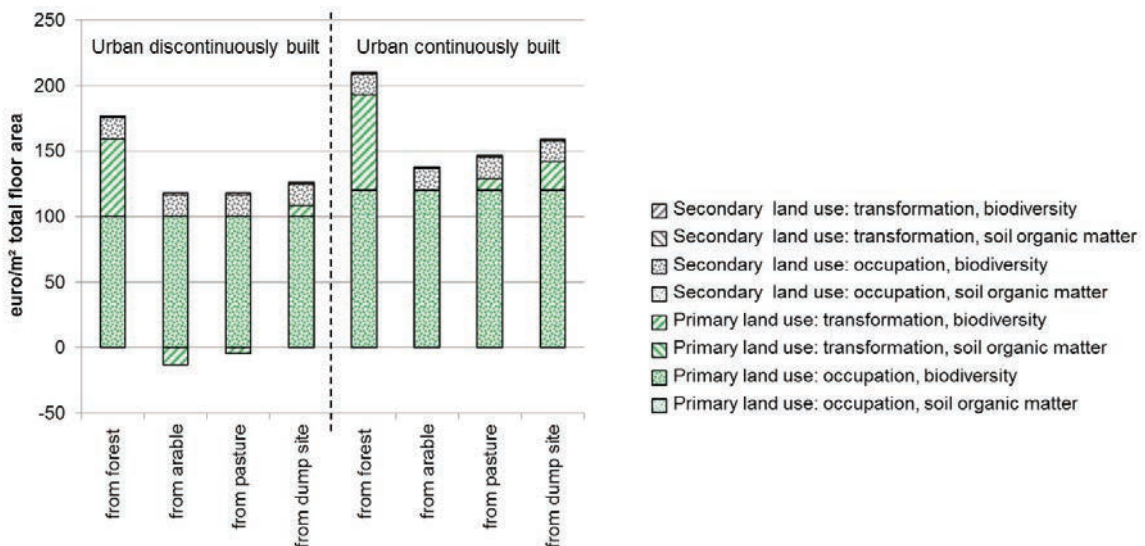


Fig. 5. Land use environmental cost of the neighbourhood model consisting of detached houses (solid structure) for different types of original and neighbourhood land use. The results are calculated based on the monetary scenario MMG\_PDF.

#### 4. Conclusions and recommendations

In this paper a method is proposed to assess the environmental impact of primary land use in neighbourhoods. This method builds upon the existing MMG LCA method, including a single score indicator, expressed in environmental cost [3][4]. The assessment of a number of neighbourhood models with diverse built densities show the high contribution of primary land use to the total neighbourhood environmental cost, especially in low built density neighbourhoods, where a contribution of up to 35% is noticed. Furthermore, primary land use results in most cases in higher environmental costs than secondary land use. Some exceptions are found for neighbourhood variants including timber frame buildings with a higher built density. Therefore we recommend to include primary land use in the life cycle assessment of neighbourhoods, especially in studies comparing different built densities.

The comparison between two sets of monetary values for the valuation of land use impacts, shows that the chosen monetisation method has a high influence on the contribution of primary land use to the total neighbourhood environmental cost but also on the ratio between primary and secondary land use in timber frame variants. Moreover the preference between solid and timber frame variants depends on the selected monetary values. In this study, the monetisation of biodiversity impacts, based on the loss of species (PDF), proved to provide a bigger differentiation between different land use types and allows to consider both the impacts of land occupation and transformation. However additional research is required as the uncertainties related to the monetary values of land use are quite high [4].

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